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Galaxy pairs in cosmological simulations: effects of interactions on colours and chemical abundances

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Abstract. We perform an statistical analysis of galaxies in pairs in a Λ-CDM scenario by using the chemical GADGET-2 of Scannapieco et al. (2005) in order to study the effects of galaxy interactions on colours and metallicities. We find that galaxy-galaxy interactions can produce a bimodal colour distribution with galaxies with significant recent star formation activity contributing mainly to blue colours. In the simulations, the colours and the fractions of recently formed stars of galaxies in pairs depend on environment more strongly than those of galaxies without a close companion, suggesting that interactions play an important role in galaxy evolution. If the metallicity of the stellar populations is used as the chemical indicator, we find that the simulated galaxies determine luminosity-metallicity and stellar mass-metallicity relations which do not depend on the presence of a close companion. However, in the case of the luminosity-metallicity relation, at a given level of enrichment, we detect a systematic displacement of the relation to brighter magnitudes for active star forming systems. Regardless of relative distance and current level of star formation activity, galaxies in pairs have stellar populations with higher level of enrichment than galaxies without a close companion. In the case of the gas component, this is no longer valid for galaxies in pairs with passive star formation which only show an excess of metals for very close pair members, consequence of an important recent past star formation activity. In

agreement with observations, the signature of gas inflows driven by interactions can be also detected in the lower mean O/H abundances measured in the central regions of galaxies in pairs. Our results suggest that interactions play a significant role in the determination of colour and chemical properties of galaxies in hierarchical clustering scenarios, although SN energy feedback is needed to achieve a full agreement.

Key words. cosmology: theory - galaxies: formation - galaxies: evolution - galaxies: interactions.

1. Introduction

Colours and chemical abundances are two important parameters that characterize galaxies. The combination of stellar populations with different ages and metallicities produces colour distributions with particular features and correlations such as the luminosity-metallicity relation. Each galaxy has an unique evolutionary history which sets the pace of the transformation of gas into stars by establishing the collapse time, the accretion rates and the impact of interactions and mergers. On its turn, these processes regulate the metal production which can modify the cooling rates, affecting the subsequent gas accretion and star formation activity. Other important factors that could contribute to determine the astrophysical, dynamical and chemical properties of galaxies are environmental effects such as the action of tidal stripping and ram-pressure as well as interactions and mergers. Disentangling the effects of each of these processes is extremely difficult. One sucessful approach is to carry out statistical analysis of large galaxy samples with the aim at underpinning their main characteristics and their dependence on the astrophysical properties of galaxies.

Large galaxy surveys such as the 2dF Galaxy Redshift Survey (2dFGRS) and the Sloan Digital Sky Survey (SDSS) have provided new insights into the properties of galaxies in the local universe. It is accepted that galaxies are grouped in two general types: blue or red (Baldry et al. 2004 and Kauffmann et al.2004), disc-dominated or spheroid-dominated, active or passive star forming. In particular, recent detailed analysis of the colour distributions of galaxies by Baldry et al.(2004) and Balogh et al. (2004, hereafter B04) have shown that these distributions can be well described by the combination of two Gaussians over an important range of magnitudes and densities. While the Gaussians features are found to depend on luminosity so that brighter systems have redder colours, the peak locations seem not to change with local density. It is only the fraction of galaxies in the blue and in the red distributions which are found to vary with local density, with high density regions mostly populated by red galaxies. According to B04, the invariability they found in the two Gaussian distributions with local density suggests that the responsible

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process of transforming blue into red galaxies has to be very efficient to overcome the effects of environment. Recently, Driver et al. (2006) also analysed the colour distribution of galaxies in pairs in the Millenium Galaxy Catalog. They confirmed that spheroid-type galaxies tend to populate the red distribution while disc-dominated ones determine the blue distribution. Hence, these results suggest that the physical mechanism responsible of the colour properties could be also linked to a change in galaxy morphology. One possible mechanism is galaxy-galaxy interactions.

As several observational works have shown that the proximity to a companion can be statistically related to an enhancement of the star formation activity (Barton et al. 2000; Lambas et al. 2003; Nikolic et al. 2003), regardless of environment (Alonso et al. 2005, 2006). The results found in these works agree with the theoretical understanding that interactions can drive strong torques which may trigger gas inflows and violent star formation (e.g. Martinet 1995). Kewley, Geller & Barton (2005) also studied galaxies in pairs but focusing on the effects of interactions on the metallicity properties of these galaxies. At a given luminosity, they found a trend for a lower enrichment in the central regions of galaxies with a close neighbour than in those of field galaxies. The relation between luminosity and metallicity (LMR) is well-known in the local universe being followed from dwarf galaxies to elliptical galaxies. Recent works from the SDSS have confirmed with outstanding statistical level the slope and zero point of this correlation at $z = 0$ (Tremonti et al. 2004 and references therein). When luminosity is substitued by stellar mass a more fundamental relation appears. The mass-metallicity relation (MMR) was first determined by Lequeux et al. (1979) and then confirmed by Tremonti et al. (2004). New observations at high redsfhit suggest an evolution for both the LMR and MMR in both zero point and slope (Kobulnicky & Kewley 2004; Liang et al. 2004; Savaglio et al. 2005; Erb et al. 2006). An statistical analysis of the metallicity properties of galaxies in pairs is still missing (Alonso et al., in preparation).

In the current cosmological paradigm, galaxies formed by the aggregation of substructure, implying that mergers and interactions are common events in galaxy formation. Many important works have been advocated to the study of the effects of interactions and mergers by using numerical simulations as first discussed by Toomre & Toomre (1972). Numerical simulations have been improved over time in order to include more complex physical processes such as hydrodynamics, radiative cooling and star formation (e.g. Thomas & Couchmann 1992; Navarro & White 1994; Tissera, Lambas & Abadi 1997; Springel & Hernquist 2002). Galaxy-galaxy interactions have been studied by several authors who found that tidal torques which developed during interactions could be strong and efficient enough to produce non-axisymmetrical instabilities in disc systems (e.g. Athanassoula & Sellwood 1986; Binney & Tremaine 1987; Barnes & Hernquist 1991, 1992; Christodoulou, Shlosman & Tohline 1995). As a consequence, gas inflows can be triggered feeding important new star formation activity. Tissera et al. (2002) showed

that, in hierarchical clustering scenarios, these mechanisms acted with different degree of efficiency along the evolutionary paths of galaxies, contributing to the formation of compact stellar bulges. These spheroidal components help to stabilize the systems. Later on, Scannapieco & Tissera (2003) showed that interactions and mergers could drive a morphological loop. According to these works, depending on the history of evolution of galaxies, systems may react in a different way during a merger event depending on their internal properties.

Pérez et al. (2006, hereafter Paper I) investigated the effects of galaxy-galaxy interactions in the concordance cosmological framework. Numerical simulations were perfomed by using the chemical GADGET-2 version of Scannapieco et al. (2005). In Paper I, we studied the effects of interactions on the star formation (SF) activity of galaxies analyzing its dependence on orbital parameters and local density. We found that simulated galaxies showed an enhancement of the star formation activity with proximity to a companion. This trend was proved to be in agreement with observational findings of Barton et al. (2000) and Lambas et al. (2003). In Paper I, it was also shown that proximity together with the properties of the potential well of the systems played an important role in the triggering of SF by interactions. We also detected that interactions accelerate the evolutionary process producing a larger fraction of passively, more stable systems in pairs, in agreement with recent observational results of Alonso et al. (2004, 2006).

In this paper, we continue the analysis of galaxy pairs in the Λ-CDM scenario discussed in Paper I extending our investigations to colours and metallicities. Recently, chemical evolution has been included in hydrodyamical simulations (e.g. Mosconi et al. 2001; Lia et al. 2001; Scannapieco et al. 2005) allowing the consistent description of the chemical enrichment of the baryonic matter as galaxies are assembled. Chemical properties can store fossil records of the interacting systems which can help us to confront models with observations. In this work, we focus on trying to unveil the effects of interactions on the colour distributions and metallicity properties of galaxies in pairs in the Local Universe.

This paper is organized as follows. In Section 2 we describe briefly the main characteristics of the numerical simulations and the criteria used to select the galaxy pairs. In Section 3, we discuss the role of interactions on the colour distribution of galaxies and compare our results with the observational ones. The chemical properties of galaxy pairs are analysed in Section 4. Section 5 summarizes our main findings.

2. Simulated galaxy pair catalogs

For our analysis, we use the galaxy pair (GP) catalogs defined in Paper I. Here we only summarize the main characteristics of the simulations and of the catalogs referring the

interested reader to Scannapieco et al. (2005) and Perez et al. (2005) for more details on the chemical code and pair selection, respectively.

The GP catalogs were constructed from a 10 Mpc h^{-1} cubic volume of a Λ-CDM Universe ($\Lambda = 0.7$, $\Omega = 0.3$, $H_0 = 100h$ km s^{-1}Mpc^{-1} with $h = 0.7$) run with the chemical code of Scannapieco et al. (2005) developed in GADGET-2 (Springel & Hernquist 2003). A total of 2×80^3 particles were used, yielding a dark matter mass of $M_{\rm DM} = 1.4 \times 10^8 {\rm M}_\odot h^{-1}$ and an initial mass for gas particles of $M_{\rm gas} = 2.2 \times 10^7 {\rm M}_\odot h^{-1}$. The chemical GADGET-2 describes the enrichment of the interstellar medium by Supernovae Type II (SNII) and Type Ia (SNIa). In this simulation, a Salpeter Initial Mass Function has been adopted with 0.1 and $40{\rm M}_\odot$ cut-offs. The theoretical yields of Woosley & Weaver (2005) and Thielemann et al. (1993) have been used for SNII and SNIa chemical production, respectively. Note that these simulations are consistent with an instantaneous thermalization of the SN energy which has no impact on the dynamics and the star formation history of the structure (e.g. Katz 1992).

Galactic systems were identified by using a fine-tunning friends-of-friends algorithm within virialized structures to select all baryonic bounded clumps (see Paper I for more details). A minimum stellar mass of 8×10^8 h^{-1} ${\rm M}_\odot$ for the clumps was imposed to minimize resolution problems. With this low mass cut-off, a total of 364 galactic systems were identified.

In Paper I, galaxy pairs were selected based only on a proximity criterium for two main reasons. First, for the sake of comparison with observational galaxy-pair analyses that used proximity criterium to select pairs (e.g. Barton et al. 2000; Lambas et al. 2001; Alonso et al. 2006). Secondly, because we are interested in the effects of galaxy-galaxy interactions even if they do not end being a merger event.

We used the tridimensional simulated galaxy pair catalog (3D-GP) constructed in Paper I where a distance criterium $r < 100$ h^{-1} kpc was estimated but requesting the galaxy members to exhibit enhanced star formation activity with respect to the average of the simulated galaxy sample, following the observational procedure first explained by Lambas et al. (2001). The 3D-GP catalog is made up of 88 galaxy pairs.

We also analysed the projected galaxy pair (2D-GP) catalog built up by projecting the tridimensional total galaxy distribution according to three random directions. The 2D-GP catalog comprises 677 galaxies in pairs with projected separation $r_{\rm p} < 100$ h^{-1} kpc and radial velocity $\Delta cz < 350$ km s^{-1}. The comparison between results from the 3D-GP and 2D-GP catalogs allows the determination of the effects of spurious pairs formed only by projection effects. A detailed discussion of this point can be found in Paper I.

We also define the control samples for both catalogs made up of galaxies without a close companion within the corresponding relative distance and velocity thresholds. The comparison of the properties of galaxies in pairs with those of galaxies without a close

companion selected from the same simulation allows us to unveil the effects of interactions as shown by Lambas et al. (2001).

The GP catalogs provide information on the stellar birthrate parameter b (defined as the present level of SF activity of a galaxy normalized to its mean past SF rate), the total stellar mass M_*, the fraction of stars formed in the last 0.5 Gyr F^* and the mean stellar age τ of all simulated galaxies within two optical radii. The optical radius is defined as the one that encloses 83 per cent of the baryonic matter of the system. We classify active and passive SF galaxies as those which exhibit higher or lower star formation activity in comparison with the average b parameter of the control sample ($b = 0.8$).

For each simulated galaxy, we also estimate the mean oxygen abundance (O/H) and the absolute magnitudes by considering stars (or gas) within two optical radii. Absolute magnitudes in different wavelenghts have been estimated by combining the star formation rate histories and the metal content of each simulated stellar population and convolving this information with the population synthesis models of Bruzual & Charlot (2003) as explained in more detail by De Rossi et al. (in preparation).

In order to characterize the environment of galaxies, we use the local projected density Σ defined as $\Sigma = 6/(\pi d^2)$, where d is the projected distance to the 6^{th} nearest neighbour brighter than $\mathrm{M_r} = -20.5$ and with $\Delta cz < 1000$ km s^{-1} (these limits have been taken from B04 and have been already used in Paper I).

3. Colour distribution in tridimensional galaxy pairs

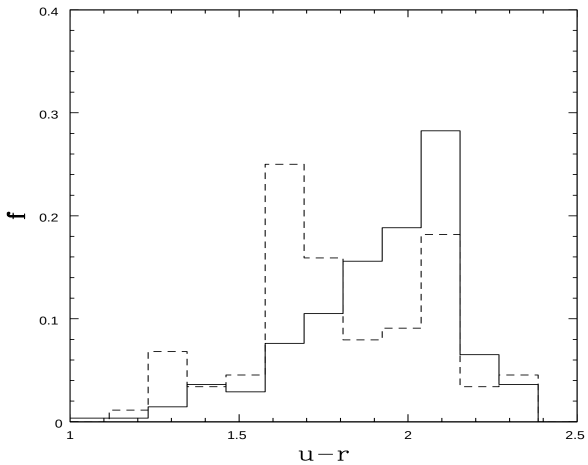
In this Section, we analyse the $u-r$ colour distribution of the simulated galactic systems for our 3D-GP sample. In order to infer the effect of interactions on the colour distribution, we also analyse the corresponding one for galaxies without a near companion (control sample). In Fig. 1 we can appreciate the colour distributions of galaxies in pairs and galaxies without a close companion displayed as histograms (upper panel) and as stellar mass partition functions (lower panel). From the results of B04, we adopt the value $u-r = 1.8$ to roughly define the limit between the red and blue distributions. We found that the mean colours of the blue and red peaks for simulated pairs (dashed line) are at $< u-r >\approx 1.6$ and $< u-r >\approx 2.1$, with 58 per cent of galaxies in the blue distribution. The control sample (solid line) has similar values: $< u-r >\approx 1.6$ and $< u-r >\approx 2.0$, but with 26 per cent of galaxies in the blue distribution. As we can see from this figure, simulated galaxies in pairs have a clear bimodal colour distribution. However, the red peaks of the simulated galaxies in pairs and in the control sample are displaced toward blue colours by ≈ 0.20 dex with respect to observations. For similar environment, B04 reported the blue mean at $< u-r >\approx 1.5$ and the red mean at $< u-r >\approx 2.3$.

In Fig. 1 (lower panel), we show the cumulative fraction of stellar mass in galaxies in pairs (dashed line) and in the control sample (solid line) as a function of colour. We

appreciate that while ≈ 60 per cent of the stellar mass in galaxies in pairs contribute to the blue colours ($u - r < 1.8$), only ≈ 30 per cent of isolated galaxies do so. According to the analysis of Kauffmann et al. (2004), blue galaxies contribute to ≈ 45 per cent of the stellar mass, averaging over all environments. Hence for the control galaxies, we found a red excess (≈ 15 per cent) which could be related to the high efficiency in the transformation of gas into stars in our simulations. Because of this, the cold and dense gas is quickly converted in stars, producing the reddening of systems. The treatment of SN energy feedback could help to regulate the SF activity preventing the artifially efficient SF activity leading to a colour distribution in full agreement with observations. However, the description of SN feedback in SPH codes is still a controversial issue and only recently a novel scheme has been presented by Scannapieco et al. (2006) which seems to be well-suited for galaxy formation in a cosmological context.

In order to get insight into the origin of the bimodal colour distribution obtained for the simulated pair sample, following Paper I we split the galaxy pairs into merging ($r < 30\ h^{-1}$ kpc) and interacting ($30\ h^{-1}$ kpc $< r < 100\ h^{-1}$ kpc) pairs. Note that the merging subsample has been named considering that their members are very close pairs and that they are physically interacting even if they are not gravitationally bounded systems.

In Fig. 2 we can appreciate the stellar mass partition function (lower panel) and colour histograms (upper panel) for both subsamples. From the colour histograms (upper panel), we estimate that 70 per cent of galaxies in merging pairs has colours $u - r < 1.8$, while only 33 per cent of interacting pairs has colours in this range. This trend is also shown by the cumulative fraction of the total stellar mass as a function of colour (lower panel). Merging pairs have ≈ 65 per cent of their stellar mass in systems with $u - r < 1.8$. In the case of interacting pairs, only ≈ 30 per cent of the stellar mass is associated to blue systems. From Paper I we know that 40 per cent of galaxies in merging pairs have enhanced SF activity with respect to galaxies without a close companion. For interacting pairs, 25 per cent of galaxies exhibit such level of SF activity. It was also proved in Paper I that for passive SF galaxies in merging systems, the fraction F^* of newly born stars increased with proximity to a companion, evidence of the higher SF level recently experienced by these systems. This analysis indicated that interactions are effective at triggering SF activity. These recently new born stars also contribute to make bluer colours as we can see from Fig. 3 where we show the fraction of recently formed stars F^* in currently active (dotted lines) and passive (dashed lines) SF galaxy pairs as a function of the $u - r$ colour. As we can see, the contribution to the blue colours comes from both active and passive SF galaxies, as long as they have experienced important star formation in the last 0.5 Gyr. A similar relation is found if pairs are divided into merging and interacting pairs, although the former have always larger F^* fractions.



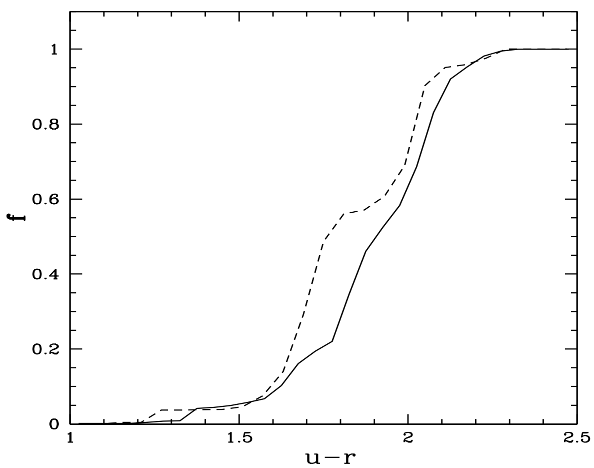


Fig. 1. Upper panel: Colour distribution for galaxies in tridimensional pairs (dashed line) and in the corresponding control sample (solid line). Lower panel: Cumulative fraction of the total stellar mass contained in these galaxy pairs (dashed line) and in the control sample (solid line) as a function of $u-r$ colour.

These findings show that galaxy-galaxy interactions are able to produce bimodal colour distributions in hierarchical clustering scenarios. Galaxies that contribute to the blue colours are those that are currently forming stars at significant high rates and those that have recently experienced strong SF activity.

4. Properties of galaxy pairs in projection

In order to directly compare the astrophysical properties of simulated galaxies in pairs with observations, we use the 2D-GP catalog. In Paper I, we estimated a 30 per cent of interlopers in pairs with $r_{\rm p} < 100\ h^{-1}$ kpc and $\Delta cz < 350$ km s^{-1}. This percentage reduces to 19 per cent for merging systems ($r_p < 25\ h^{-1}$ kpc and $\Delta cz < 100$ km s^{-1}). These findings are in agreement with those found by Nikolic et al. (2004) who studied the projection effects on galaxy pairs from the SDSS spectroscopic and photometric data,

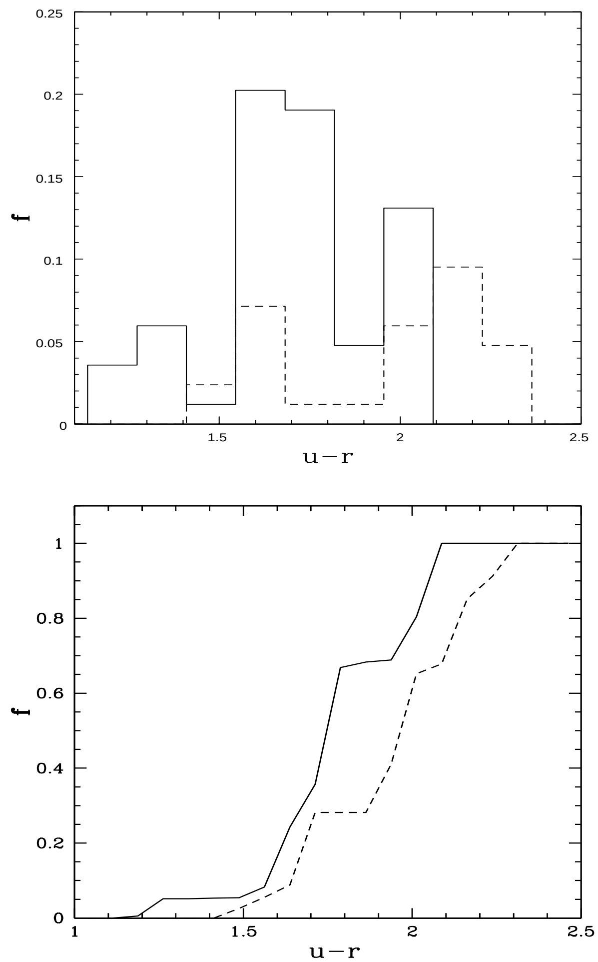


Fig. 2. Upper panel: Colour distribution for galaxies in tridimensional pairs separating in merging ($r < 30\ h^{-1}$ kpc, solid line) and interacting ($30\ h^{-1}$ kpc $< r < 100\ h^{-1}$ kpc dashed line) systems. Lower panel: Cumulative fraction of the total stellar mass contained in merging galaxies (solid line) and in interacting ones (dashed line) as a function of $u - r$ colour.

estimating a 20 per cent of spurious systems in pairs with $r_{\rm p} < 100\ h^{-1}$ kpc. We found that these fractions of interlopers do not significantly affect the results that could be derived from the 2D catalogs. For example, Fig. 4 shows the 2D (dashed lines) and 3D (solid lines) cumulative fraction of stellar mass in galaxies in pairs (upper panel) and in the control samples (lower panel) as function of $u - r$ colour. As we can appreciate, the differences are less than ≈ 10 per cent, suggesting that effects of projection do not change strongly the colour distribution of either sample. Therefore, hereafter we continue the analysis of the properties of the 2D-GP catalog because of its high statistical number.

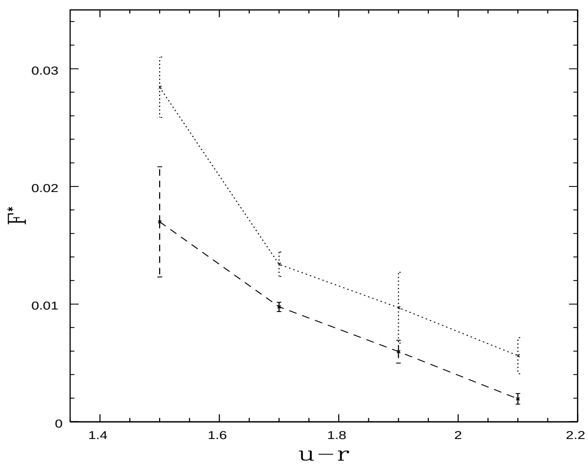


Fig. 3. Fraction of stars formed in the last 0.5 Gyr as a function of $u-r$ colour for active (dotted line) and passive (dashed lines) star forming galaxies in tridimensional pairs. Error bars have been estimated by applying the bootstrap resampling technique.

4.1. Dependence of colours and metallicities of galaxies in pairs on local density.

In this section, we analyse the dependence of colours and metallicities of galaxies in pairs on environment. The sample has been divided into a low and a high density subsamples by adopting the density threshold $\log \Sigma = -0.8$, and the magnitude limit of $M_r = -18$ (B04) used in Paper I.

We estimated the cumulative fraction of the total stellar mass contained in galaxies with and without a close companion as a function of colour in the two defined environments. As seen from Fig. 5, we found the expected trend for a larger fraction of stars contributing to build up red galaxies in pairs and in the control sample in high density regions. This trend is in agreement with the results found by Kauffmann et al. (2004) for the SDSS catalog.

From Fig. 5, we can also see that the fraction of stellar mass contributing to red galaxies increases more strongly with local density if the systems are in pairs. In high density regions, a fraction of ≈ 0.70 of the stellar mass in pairs is found in systems with colours redder than $u-r = 1.8$ while this fraction decreases to 0.55 in low density regions. For galaxies without a close companion the fractions of stellar mass contributing to colours redder than $u-r = 1.8$ are very similar in both regions. Nevertheless, the effects of environment for the control sample can be seen in the absence of stellar mass in galaxies with $u-r < 1.6$ in high density regions.

In Fig. 6 we estimate the cumulative fraction of stellar mass for galaxies in pairs as a function of the mean O/H abundance of the stars (a), the mean stellar age (b) and the fraction F^* of recenty new born stars (c), for high and low density environments. Similar estimations were carried out for galaxies in the control sample (right panels).

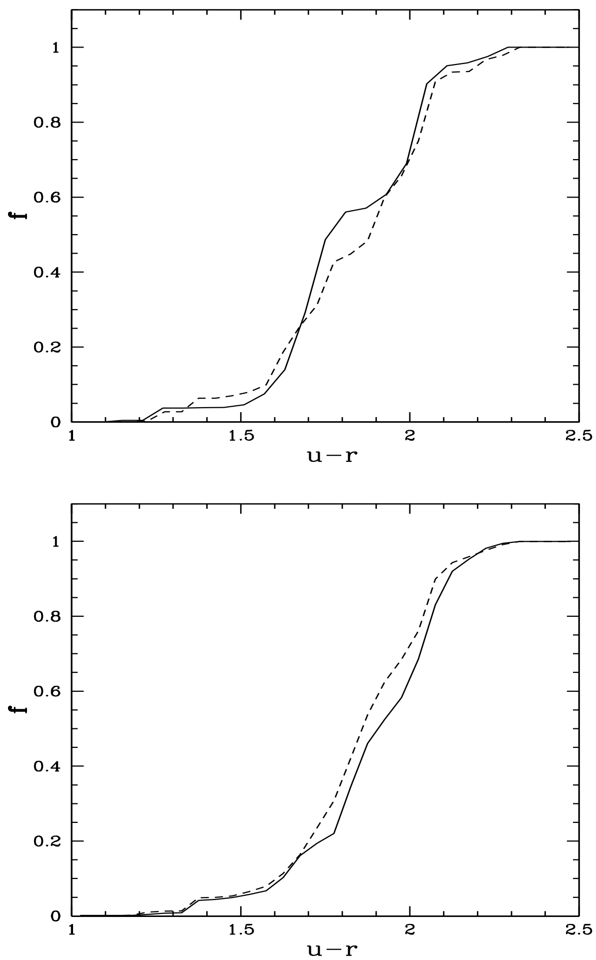


Fig. 4. Cumulative fraction of the total stellar mass contained in galaxies as a function of $u-r$ colour, in pairs (upper panel) and in the control samples (lower panel) constructed from the tridimensional (solid lines) and projected (dashed lines) total simulated galaxy catalogs.

In the case of the mean stellar age, galaxies in the control sample have a younger underlying stellar population in low density regions, with ≈ 60 per cent of the stellar mass younger than 10 Gyr. In high density regions, this percentage goes down to 35 per cent. Galaxies in pairs have underlying stellar populations with similar mean ages in both environments with ≈ 50 per cent of the stellar mass having a mean age of less than 10 Gyr (consistently with the trend of galaxies in the control sample in low environments).

The mean metallicity of the global stellar population shows a similar trend for galaxies in pairs and in the control samples. Galaxies without a close companion contribute with more stellar mass to the low metallicity end (by approximately a factor of two) than galaxies in pairs. Finally, the fraction of recently new born stars (F^{*}) unveils the effects of interactions and its dependence on environment very clearly. Galaxies in pairs in low density regions have larger fractions of recently formed stars with respect to their counterparts in higher density environments and to galaxies without a close companion.

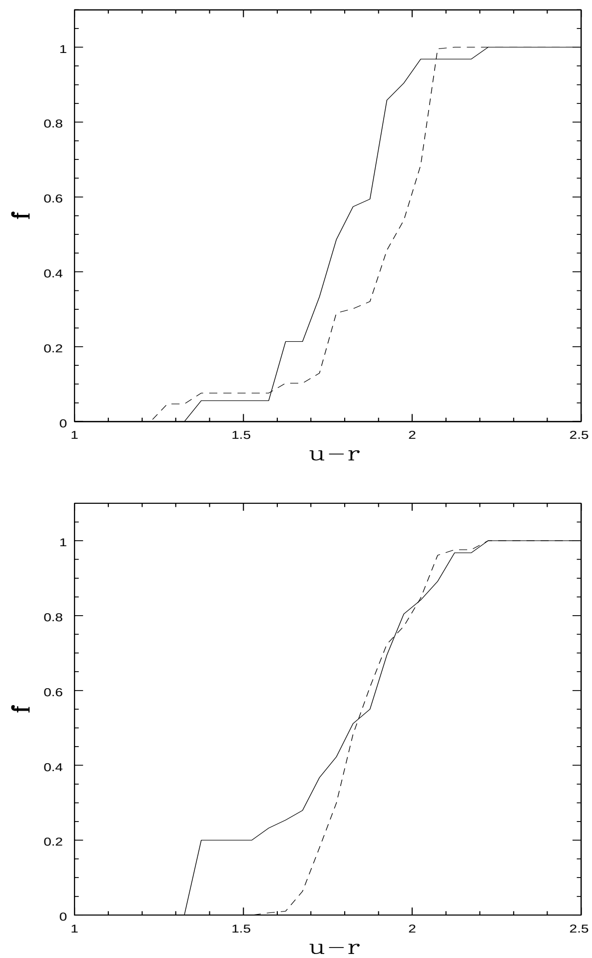


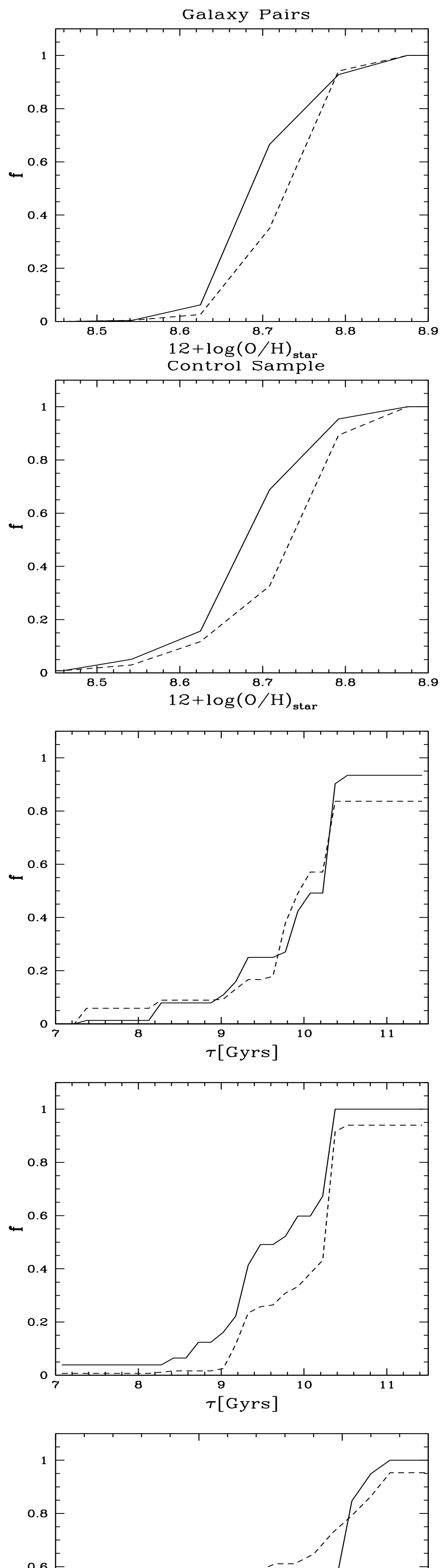
Fig. 5. Cumulative fraction of the total stellar mass contained in galaxies as a function of u-r colour. Projected galaxies in pairs (upper panel) and in the control samples (lower panel) have been separated in low (solid lines) and high (dashed lines) density regions.

Overall, we can appreciate that, in low density regions, galaxies in pairs tend to be less metal-enriched and to have a significant higher amount of recently born stars with respect to pairs in high density environments.

4.2. Chemical properties of galaxies in pairs

The chemical properties of the stellar populations (SP) and the interstellar medium (ISM) can store information on the evolution of galaxies. In particular, mergers and interactions could imprint metallicity features that might provide valuable information about their evolution.

In Fig. 7, we show the mean O/H abundances of both the SPs (a) and the ISM (b) of galaxies in pairs (solid lines) in the simulated 2D-GP catalog as a function of the projected separation. Galaxies were also divided according to their star formation activity in active star-forming (dotted lines) and passive star-forming (dashed lines) systems.



Galaxy Pairs
f
$12+\log(O/H)_{star}$
Control Sample
f
$12+\log(O/H)_{star}$
f
τ[Gyrs]
f
τ[Gyrs]

The horizontal lines represent the corresponding mean values for galaxies without a close companion divided in a similar fashion.

From Fig. 7a we observe that the mean abundances of the SPs in passive SF galaxies in pairs show an enhancement of their chemical abundances with respect to the corresponding mean of the control sample for all projected distances. Active SF galaxies in pairs show an enhancement of the abundances of their SPs with respect to the mean abundance of the control sample but at a lower level in comparison to passive SF systems.

In Fig. 7b we can see the abundances of the ISM for galaxies in pairs. We find that, regardless of the presence of a close neighbour, active SF systems in pairs show ISMs with higher levels of enrichment. On the other hand, currently passive star forming galaxies in pairs show a clear correlation of their ISM O/H abundances with relative distance, fossils of recent past interactions. This correlation can be understood analysing the recent past SF history of these systems. As it can be seen from Fig. 8, the F^{*} fraction for passive SF galaxies in pairs anticorrelates with the relative distance to the nearest neighbour. Systems with a very close neighbour that have their gas components chemically enriched (Fig. 7b), have experienced star formation within the last 0.5 Gyr.

It is important to note that so far O/H abundances have been estimated within two optical radii providing information on the overall metallicity of baryons, in form of stars or gas, associated to the simulated galaxies. Recent observational results on the metallicity properties of pairs by Kewley et al. (2005) showed a decrease in the O/H abundance measured in the central regions of close galaxy pairs compared to galaxies without a close companion. These authors interpreted this finding as a result of low metallicity gas inflows driven by the tidal torques generating during the interactions (e.g. Barnes & Hernquist 1992, 1996). In order to investigate this point in our simulations, we estimated the O/H abundances within the central region of the simulated galaxies defined within 0.5 $r_{\rm opt}$ for close pairs. In Fig. 9 we have plotted the gas O/H abundances in the central regions (solid line) and within two optical radii (dashed line) of galaxies in pairs with relative distances lesser than 50 kpc h^{-1} and the mean O/H abundance of galaxies in the control sample (horizontal line). As it can be observed the central regions show lower level of enrichment with respect to the mean O/H abundance of the control sample. The decrease in the mean O/H abundances is produced by the contribution from the gas inflows from the external regions which also trigger star formation activity as shown in Paper I.

We also estimated the LMR for our simulated samples by using the overall mean stellar O/H abundances (i.e. measured within 2 $r_{\rm opt}$). Although galaxies with and without a close companion exhibit the same trend for their LMR, a difference of 0.75 mag in the zero point of the LMRs is dectected if galaxies are splitted according to their current SF activity into passive and active ones as shown by Fig. 10. We note that the simulated LMR has a similar slope to the observed relation although with a higher overall level

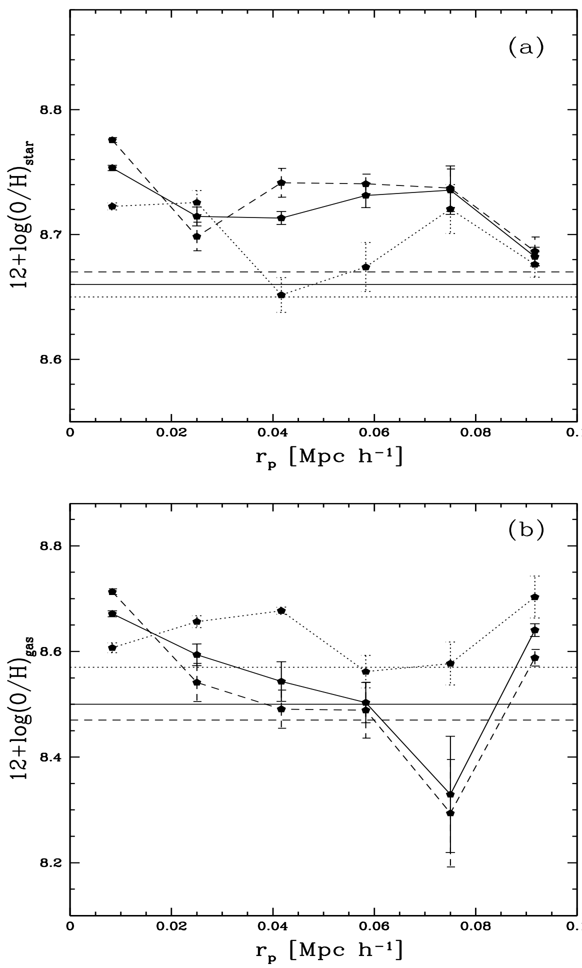


Fig. 7. Oxygen abundances for the stellar populations (a) and the interstellar medium (b) as a function of projected distance to the closest neighbour, separated in active SF (dotted lines), passive SF (dashed lines) and all (solid lines) galaxies in pairs. The corresponding mean abundances for galaxies in the control sample are shown as horizontal lines. Error bars have been estimated by applying the boostrap resampling technique.

of enrichment. A possible source for this discrepancy could be due to the fact that we have used mean stellar O/H abundances for all simulated galaxies because they are less affected by numerical noise. Meanwhile, observations normally use abundances of the gas phase in HII regions of star forming galaxies. This does not invialidate our reasoning since both simulated samples have been selected from the same simulation. Nevertheless, the aim of this work is not to study the observed LMR but to assess if simulated galaxies in pairs have a different LMR when compared to galaxies without a close companion. The reader is refered to De Rossi et al. (in preparation) for an extensive discussion on the LMR of galaxies in Λ-CDM scenarios. Finally, we also estimated the MMR for the same systems finding, in this case, no difference for active or passive SF galaxies (with

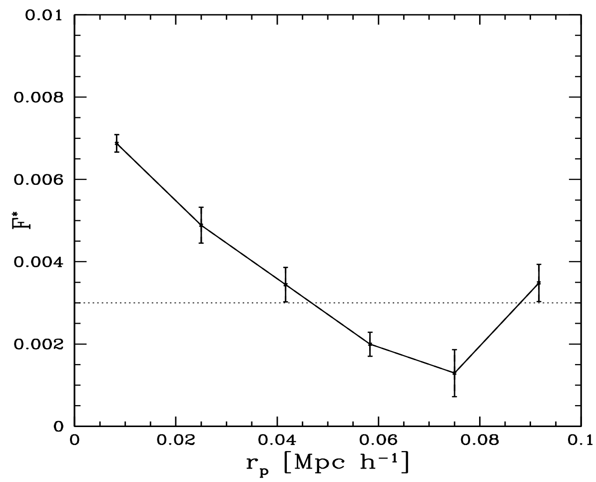


Fig. 8. Fraction (F_*) of stars formed in the last 0.5 Gyr as a function of the relative separation for currently passive star forming galaxies in pairs. The horizontal line represents the mean value of F_* for the currently passive star forming galaxies without a close companion. Boostrap errors are given.

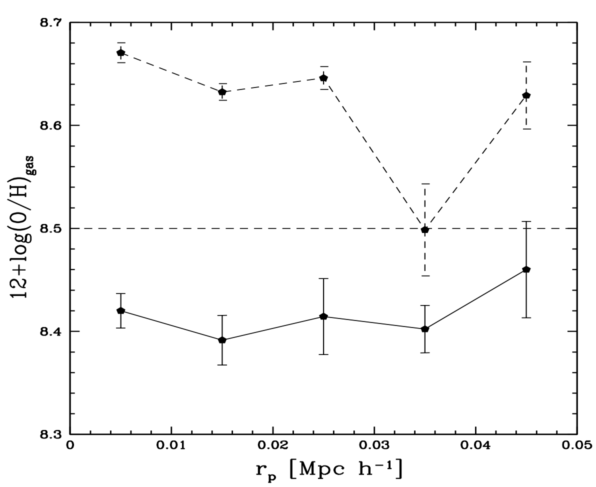


Fig. 9. Mean O/H abundances of the insterstellar medium in galaxies in pairs estimated within 0.5 $r_{\rm opt}$ (solid line) and 2 $r_{\rm opt}$ (dashed line) as a function of relative separation. The horizontal line represents the mean O/H abundance for the control sample.

and without a companion) as it can be appreciated in the inset box of Fig. 10[1]. Both results suggest that stellar mass is a more fundamental parameter than luminosity. In fact, this claim has been driven from observational (e.g. Tremonti et al. 2004; Erb et al. 2006) and from numerical (Tissera et al. 2005) works. This lack of dependence of mean metallicity on stellar mass suggests that the displacement of the LMR for galaxies with

[1] The simulated MMR has a different slope than that reported by Tremonti et al. (2004) for stellar masses lower than $10^{10} M_{\odot} h^{-1}$. At lower masses, these simulations show an excess of metals due to the lack of strong SN feedback (Tissera, De Rossi & Scannapieco 2005).

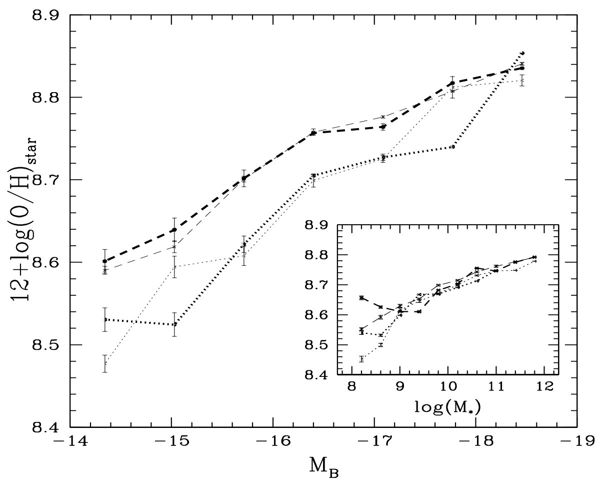


Fig. 10. Simulated luminosity-metallicity relation for active (dotted lines) and passive (dashed lines) SF systems in pairs (thick lines) and in the control sample (thin lines). In the inset box we show the stellar mass-metallicity relation for the same samples.

different level of SF activity is produced mainly by the increase in the luminosity in those actively forming stars, at a given mean stellar metallicity level.

5. Conclusions

In this work we analyse galaxies in pairs in cosmological simulations in a Λ-CDM scenario as a continuation of the work presented in Paper I. We study colours and metallicity properties of simulated galaxies with and without a close companion in order to unveil the effects of galaxy-galaxy interactions. We find that spurious pairs affect weakly the colours and the metallicity properties of galaxies in pairs.

We obtain that interactions are able to induce a bimodal colour distribution where the contribution to blue colours comes from those galaxies with recently significant star formation activity. Red galaxies are formed, on average, by old stars ($\tau > 10$ Gyr) which have experienced no significant star formation activity in the last 0.5 Gyr. Galaxies without a close companion contribute with less stellar mass to the blue colours. This red excess is produced by the efficient transformation of gas into stars in our simulations due to the lack of a self-consistent supernova feedback model that could help to regulate the star formation process (Scannapieco et al. 2006). The analysis of merging and interacting pairs shows that the former contributes with a larger fraction of blue stellar mass than the latter, demostrating the ability of interactions in driving a colour bimodality.

The fraction of stellar mass in red galaxies increases with local density and this effect is stronger if the galaxy has a close companion. These results are consistent with our previous analysis of the SF activity in different environments discussed in Paper I which showed that the fraction of passive SF systems in pairs in high density regions exceeds that observed in galaxies without a close companion. The excess of stellar mass with red

colours in galaxies in pairs detected in our simulations is also in agreement with recent observational results (De Propis et al. 2005; Alonso et al. 2006).

The ISMs of galaxies with active SF is highly enriched regardless of the presence of a close companion. However, the abundances of the ISMs of galaxies in pairs with passive SF activity shows a dependence on proximity to the nearest neighbour. A similar dependence is found for the fraction of recently formed stars in these systems. Hence, while the chemical properties of galaxies with strong SF activity show an excess of metals at all distances, those of passive SF systems anticorrelates with spatial proximity. This anticorrelation could store fossil records of interactions and could be, then, used to unveil recent SF episodes. If central mean O/H abundances are measured, then, we detect a decrease in the metallicity level for closer galaxy pairs produced by the increase of low metallicity gas inflows driven during the interactions. These gas inflows are responsible of the increase in the star formation activity reported in Paper I and studied in detail by other authors (e.g. Mihos & Hernquist 1996; Barnes & Hernquist 1992, 1996; Tissera 2001; Tissera et al. 2002).

If we use the abundances of the SPs as a chemical indicator, we found that the MMR of galaxies in pairs and galaxies without a close companion are very similar, regardless of the SF activity of the systems. This finding suggests that the stellar mass is determining the metallicity content of a galaxy, at least, when no strong galactic winds are present. The LMR of galaxies in active SF in pairs and in the control sample show a displacement towards brighter mangitudes by ≈ 0.75 mag with respect to those systems passively forming stars. The results obtained by using the chemical abundances of the ISM as a chemical indicator are quite noise making difficut to draw any conclusion.

Our analysis suggests that galaxy-galaxy interactions can significantly contribute to the determination of the bimodal colour galaxy distribution and chemical relations. In particular, the strong dependence of the astrophysical properties of galaxies in pairs on environment suggests that interactions are an efficient process of transforming galaxies considering that the rates of mergers and interactions increase with local density in hierarchical clustering scenarios. The agreement between these results and recent observational findings supports the current cosmological paradigm for galaxy formation while the discrepancies suggest the need for strong SN feedback.

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